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Detecting Dark Matter in High Velocity Clouds

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ABSTRACT

Many high velocity HI clouds (HVCs) are now believed to be scattered throughout the Galactic halo on scales of tens of kiloparsecs. Some of these clouds appear to contain substantial HI masses ($> 10^6 M_\odot$). It has been suggested that these structures may be associated with dark matter 'mini halos' accreting onto the Galactic halo. For a compact HVC along the sight line to a more distant galaxy, we demonstrate that 'pixel gravitational lensing' provides a crucial test for the presence of a dark halo in the form of massive compact objects. The detection of pixel lensing will provide an independent means to map the mass distribution within HVCs.

Subject headings: High Velocity Clouds; Dark Matter; Gravitational Microlensing

1. INTRODUCTION

Observations of the Galactic halo make a compelling case that the formation of halos continues to the present day (Wyse 1999). The halo appears to have built up through a process of accretion and merging of low-mass structures which is still going on at a low level. Hierarchical cold dark matter (CDM) simulations, however, predict that the Galactic halo should have many more satellites than are actually observed (Klypin *et al.* 1999; Moore *et al.* 1999). Observations reveal that much of the sky is peppered with high-velocity HI clouds (HVCs) which do not conform to orderly Galactic rotation. These are interesting accretion candidates – particularly if they are associated with dark matter 'mini halos' – except that their distances, d, are unknown for all but a few sources. As a result, fundamental physical quantities – size ($\propto d$) and mass ($\propto d^2$) – are unconstrained which has encouraged wide speculation as to the nature of HVCs (Wakker & van Woerden 1997; 1999).

The current renaissance in HVC studies can be traced in part to one paper. Blitz *et al.* (1999) have shown that the velocity centroids and groupings of positive/negative velocity clouds on the sky may be understood within a reference frame centered on the Local Group barycenter. They interpret HVCs as gas clouds accreting onto the Local Group over a megaparsec sphere. Braun & Burton (2000) have identified specific examples of compact clouds that have 'rotation curves' consistent with CDM mass profiles. For sources at 700 kpc, the kinematic signatures imply a high dark-to-visible mass ratio of 10–50.

However, Zwaan & Briggs (2000) note from the Arecibo HI Strip Survey that of 300 galaxies and 14 galaxy groups, none appear to have properties resembling HVCs associated with the Milky Way or the Local Group. A possible interpretation is that the clouds are somewhat closer to the galaxy or group barycenters.

Reliable distance indicators for HVCs are presently hard to come by. Oort (1966) proposed virial distances on the assumption that HVCs are self-gravitating. The mass inferred from the HI column density has a different distance dependence to the gravitationally inferred mass from the HI line width. This crude method puts some

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HVCs at megaparsec distances (Blitz *et al.* 1999; Braun & Burton 1999). An alternative method is to use bright sources with well-calibrated distances along the sight line to gas clouds. If the cloud produces absorption in the spectrum of one source but not in the other, the cloud distance can be bracketed. This method establishes that two HVCs are within 10 kpc of the Sun (van Woerden *et al.* 1999).

We have recently developed the Hα distance method which has the potential to reach much greater distances (Bland-Hawthorn *et al.* 1998; Bland-Hawthorn & Maloney 1999a,b). If a gas cloud is optically thick to ionizing radiation from a source with known luminosity, the Hα flux can be used to infer the external field strength and therefore the cloud's distance from the source. Two groups have now used this method to show that many HVCs are faint or invisible in Hα and appear to be distributed on scales of tens of kiloparsecs throughout the Galactic halo. Some of these clouds have HI masses in excess of $10^6 M_\odot$ (Weiner *et al. in preparation*; Putman *et al. in preparation*).

In establishing whether the HVCs are truly candidates for merging 'mini halos', their dark matter content needs to be determined. By considering their potential gravitational lensing properties, we now describe a test to establish whether compact HVCs do indeed contain such dark matter halos.

2. GRAVITATIONAL LENSING

2.1. MASS PROFILE

Utilizing an extensive sample of numerical simulations, Navarro, Frenk and White (1997) (NFW) recently suggested that the density profile of dark matter halos formed within the framework of cold dark matter cosmology can be simply described as

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_s}{(r/r_s)(1+r/r_s)^2} \qquad (1)$$

where r_s is a scale radius which is related to the r_{200} (the radius of the halo within which the average is 200$\times$ the critical density of the Universe, ρ_{crit}), by a 'concentration' c_s, such that $r_{200} = c_s r_s$. The (dimensionless) characteristic density, δ_s, is simply related to c_s by

$$\delta_s = \left(\frac{200}{3}\right) \frac{c_s^3}{[\log(1+c_s) - c_s/(1+c_s)]} \; . \qquad (2)$$

We adopt this profile in describing the dark matter distribution in HVCs. For a particular halo mass, defined as $M_{200} = M(< r_{200})$, the concentration c_s depends on the halo collapse redshift, and hence the cosmology, power spectrum etc. Assuming $\Omega_o = 1$ & $\Lambda_o = 0$, we employ the recipe provided by NFW to determine the halo profiles in a standard CDM cosmology. A numerical routine for calculating these properties was kindly provided by Prof. Navarro.

Bartelmann (1996) and Wright & Brainerd (2000) have considered the gravitational lensing properties of massive galaxy clusters with NFW mass profiles. Rather than the radial density distribution (Equation 1), the important quantity in such an analysis is the projected surface mass density. This is given by

$$\kappa(x) = 2\kappa_s \frac{f(x)}{x^2 - 1} \qquad (3)$$

where $x = r/r_s$. The normalizing factor is given by $\kappa_s = \delta_s r_s \rho_{crit}/\Sigma_{crit}$, where Σ_{crit} is the critical surface mass density to gravitational lensing;

$$\Sigma_{crit} = \frac{c^2}{4\pi G} \frac{D_{os}}{D_{ol} D_{ls}} \qquad (4)$$

where D_{ij} are the angular diameter distances between the observer (o), lens (l) and source (s). The auxiliary function $f(x)$ is given by

$$f(x) = \begin{cases} 1 - \frac{2}{\sqrt{1-x^2}}\, arctanh\sqrt{\frac{1-x}{1+x}} & (x < 1) \\ 0 & (x = 1) \\ 1 - \frac{2}{\sqrt{x^2-1}}\, arctan\sqrt{\frac{x-1}{x+1}} & (x > 1) \end{cases} \qquad (5)$$

Defining $g(x) = f(x)/(x^2-1)$, the normalised surface mass density is given by;

$$\kappa(x) = 3.33 \times 10^{-13} \frac{\delta_s}{c_s} r_{200} D_{ol} \left(1 - \frac{D_{ol}}{D_{os}}\right) g(x) h^2 \qquad (6)$$

where all distances are in kpc, and it is assumed that only objects in the local Universe are considered, such that $D_{ls} = D_{os} - D_{ol}$. The Hubble parameter, h, is defined such that $H_o = 100h\ km/s/Mpc$.

2.2. LENSING PROPERTIES

Armed with these various tools, we can now examine the gravitational lensing properties of dark matter halos of HVCs. Considering fiducial masses of $M_{200} = 10^6, 10^7, 10^8$ & 10^9 $M_\odot$, corresponding to the potential dark matter masses of HVCs, we determined the NFW parameters; these are summarized in Table 1. Firstly, it is important to determine whether the projected surface density of these dark matter halos is sufficient to induce macrolensing effects, resulting in multiple images; in the absence of strong shearing, this requires the normalized surface mass density, κ to exceed unity. An examination of Equations 3 and 5, reveals that $\kappa(x)$ becomes singular at $x = 0$ and must meet the criterion for producing multiple images at some radius. At small x, the surface density becomes

$$\kappa(x) \sim 2\kappa_s \log\left(\frac{2}{e}\frac{1}{x}\right) . \qquad (7)$$

Considering the parameters in Table 1, and placing the HVC at any reasonable distance, $\kappa(x)$ does not exceed unity until very small (and unphysical) radii. Therefore, such halos are unable to produce observable macrolensing effects and the dark matter cannot be probed by looking for 'image splitting' of distant sources. However, if the dark matter in HVC is in the form of compact objects, these will introduce microlensing variability into the observations of background sources. As potential source are extragalactic, namely galaxies, the resulting microlensing is unlike that in the Magellanic Clouds and the Galactic Bulge, where an individual star is seen to brighten and fade as a compact object crosses the line-of-sight. Rather, as a patch of light from a distant galaxy represents an unresolved population of stars, any microlensing will be seen as against this smooth background. Hence, microlensing will be detected as fluctuations in surface brightness over the source galaxy. The framework of this 'pixel-lensing' was laid down by Crotts (1992) and Gould (1996), and has recently proved successful in a search for compact objects along the lines of sight to M31 and the Galactic Bulge (Crotts & Tomaney 1996; Tomaney & Crotts 1996; Alcock *et al.* 1999). Pixel lensing has also been proposed as a tool to search for both intracluster compact objects (Gould 1995; Lewis, Ibata & Wyithe 2000) and cosmologically distributed dark matter (Lewis & Ibata 2000).

M_{200}	δ_s	c_s	r_{200}
10^6	1.66×10^6	40.95	1.63
10^7	1.21×10^6	36.40	3.51
10^8	8.61×10^5	31.95	7.57
10^9	5.87×10^5	27.60	16.30

Table 1: The parameters of the NFW density profile, for several fiducial values of M_{200} (in units of $M_\odot$), corresponding to the potential dark matter masses of HVCs. While δ_s and c_s are dimensionless, r_{200} is in kpc. These values were calculated assuming $h = 1$.

Using Equation 6, and considering the NFW parameters presented in Table 1, the microlensing optical depths for the dark matter halos can be calculated. By assuming that the halo lies at a distance of 100kpc from the Earth, in front of a source at 3Mpc, Table 2 presents the optical depths at several angular radii. It is immediately apparent that the optical depths for all the models are small, in the regime probed by the microlensing searches towards the Galactic Bulge and halo. Given the subcritical value of the microlensing optical depth seen through the dark matter halos associated with the HVCs, the expected number of 'pixel-lensing' events simply scales as $\Gamma \propto \kappa$ (see Binney 2000). Hence, in searching for HVC compact dark matter objects objects, a simple test presents itself; in monitoring the surface brightness distributions of galaxies, regions that overlap with the dark matter halos of HVCs will display pixel-lensing variability. Moreover, as the optical depth increases towards the center of the HVC systems, the resultant number of microlensing events should also increase towards the center. Given the simple linear scaling between the number of events and the surface mass density, the identification of microlensing of systems viewed through HVCs will not only detect the dark matter component, but will also provide a (non-kinematic) map of the dark matter mass over tens to hundreds of arcseconds, depending upon the mass of the halo. A detailed calculation of the optical depth distribution for specific HVCs and source galaxies is beyond the scope of this current paper and will be presented elsewhere. A simple estimate of the expected number of events can be found by extrapolating the analysis of Binney (2000), who determines that for an optical depth of $\kappa = 10^{-6}$ and sources at 50 Mpc, monitoring with a 4-m class (diffraction limited) telescope will uncover three or four events per 10^6 resolution elements per week. For a similar source distance, and a HVC located at 100 kpc, the optical depth in the central regions of the halos presented in this paper are greater than 10^{-6}, with the $10^9\ M_\odot$ exceeding this by a factor of ~ 50 over a region $10''$ in radius. Increasing the distance to the HVC will similarly increase the number of expected microlensing events. This analysis indicates that if HVCs are enshrouded in halos of compact dark matter, then a substantial number of microlensing events should be detectable.

One potential contaminant is microlensing of the sources by compact objects within our own Galactic halo, or that of the potential source. Binney (2000) recently examined the sky distribution of halo microlensing optical depth to distant sources within several models for the mass distribution of the Galaxy. The optical depth is greatest in the disk of the Galaxy, and falls rapidly with Galactic latitude, falling below 10^{-6} for $|b| \gtrsim 12^o$. At these higher galactic latitudes even the least massive halo considered in this paper will dominate the microlensing optical depth along a line-of-sight by a factor of ten. Similarly, the optical depth through the halo of the source will also be of order 10^{-6}, and show a similar distribution over the galaxy. Microlensing by material in the HVC halo will enhance this value, and will be spatially correlated with the HVC core, making in discernible from any intrinsic 'self-lensing'.

Recent results from the MACHO (Alcock et al. 2000) and EROS (Lasserre et al. 2000) studies towards the Magellanic Clouds suggest that only $\sim 20\%$ (at most) of the dark matter halo of the Galaxy resides in the form of compact objects. If this is the case, and the distribution of dark matter is universal, then the optical depths presented for the HVCs would have to be scaled by a similar factor. However, if the dark matter in the Galactic halo is clumped on large scales then our view to the Magellanic Clouds may be through a relatively empty region. Such a picture, which is consistent with the hierarchical accretion model discussed in this paper (see Klypin et al. 1999), may explain why our view towards the Galactic Bulge appears to be relatively overdense in MACHOs (Binney, Bissantz & Gerhard 2000; Alcock et al. 2000a).

3. PROPOSED EXPERIMENT

The practical limitations to the pixel lensing technique described in Section 2 are, of course, set primarily by the availability, or lack thereof, of (purported) dark matter-dominated HVCs suitably aligned with background galaxies. To a $5\,\sigma$ limiting H I column density of $7{\times}10^{17}\,\mathrm{cm}^{-2}$, Murphy et al. (1995) claim an HVC sky covering fraction of $\sim$37%. The high detection rate of high-velocity Galactic Mg II gas seen toward background quasars (Savage et al. 1993) implies a covering fraction of $\sim$50% at column densities of $2{\times}10^{17}\,\mathrm{cm}^{-2}$. Clearly, high-velocity gas does exist, at some level, along virtually all extragalactic sightlines. Unfortunately, one needs to exercise restraint before proclaiming that the pixel lensing experiment will therefore be a trivial one.

Of greatest concern is the potential contamination due to the inclusion of "non-dark matter-dominated HVCs" in the above sky covering fractions. Eliminating large, diffuse, HVCs from the above sample (e.g. Magellanic Stream, Complexes A, C, and M), and restricting the analysis to unresolved ($<$1 deg^2), isolated, HVCs, immediately reduces the covering fraction by a factor of $\sim$50 – to $\sim$0.7% – Blitz & Robishaw (2000). An even more stringent sampling was adopted by Braun & Burton (1999) in constructing their Compact High-Velocity Cloud (CHVC) catalog, resulting in a compilation of only 65 candidates. Subsequent high-resolution imaging of a subset of these CHVCs (Braun & Burton 2000) shows that each is $\sim$0.2 deg^2 in areal extent, for a total sky covering fraction of $\sim$0.03% – more than three orders

M_{200}	$1''$	$10''$	$100''$
10^6	8.5×10^{-6}	3.8×10^{-6}	5.4×10^{-7}
10^7	1.8×10^{-5}	9.9×10^{-6}	2.5×10^{-6}
10^8	3.8×10^{-5}	2.3×10^{-5}	8.8×10^{-6}
10^9	7.4×10^{-5}	4.9×10^{-5}	2.4×10^{-5}

Table 2: The optical depths of dark matter halos as a function of radius for the fiducial masses considered in this paper. The halo is placed at a distance of 100kpc, in front of a source at 3Mpc. At this distance, $100''$ corresponds to 48.5pc. The optical depths can be scaled to other distances using Equation 6.

of magnitude lower than that found by Murphy et al. (1995). The southern sample of CHVCs in the Braun & Burton catalog was necessarily limited to the older H I survey by Bajaja et al. (1985); this has since been supplanted by the Morras et al. (2000) survey (a direct southern analog to the Leiden-Dwingeloo Survey - Hartmann & Burton 1997) and the H I Parkes All Sky Survey (HIPASS – Putman & Gibson 1999a,b). This latter survey is particularly attuned to the discovery of CHVCs, as it is the first of its kind to sub-Nyquist sample the southern sky. A visual inspection of several random HIPASS data cubes demonstrates that a factor of two increase in the number of known southern CHVCs (with H I column densities $>10^{18}\,\mathrm{cm}^{-2}$) can be expected.

As Blitz & Robishaw (2000) demonstrate, the probability of a chance alignment of a CHVC with a nearby, background galaxy is $\sim$ 1%. Even allowing for the aforementioned expected increase in the number of catalogued CHVCs, this probability will remain <2%. On the other hand, *if* the simulations of Klypin et al. (1999) and Moore et al. (1999) are correct, one might expect there to be 300−500 CHVCs in the Local Group, of which only ∼100 have been accounted for. Perhaps deeper H I surveys will uncover this missing population, or perhaps they will only be discovered serendipitously through studies of background quasars. Regardless, the inclusion of this additional hidden population of CHVCs, would increase the probability of finding a CHVC-background galaxy alignment to 3−5%.

Obviously, this will be a challenging experiment, but not an impossible one. We are initiating a search through the HIPASS data cubes, in an attempt to uncover prospective candidates. Several possibilities currently exist, although we stress this is neither a finalized nor complete list – HIPASS 1328−30 (Banks et al. 1999) and ESO 383-G087, both in the Cen A Group, NGC 3109, in the Antlia-Sextans Grouping, and NGC55 & AM0106-382 in Sculptor, each have CHVCs lying within $15'$-$30'$, yet kinematically separated, from the galaxy.

4. CONCLUSIONS

Cold dark matter models for the formation of universal structure predict that the Galaxy should be be surrounded by many infalling 'clumps' of material. While the Galaxy is accompanied by a number of dwarf galaxies, they cannot account for the total expected population of objects. Recently, it has been suggested that high-velocity clouds are accompanied by halos of dark matter and hence represent, and trace, the missing dark matter population.

In this paper we have demonstrated that while HVCs are too diffuse to produce macrolensing splitting of distant sources, if their dark matter consists of compact object, then this adds to the microlensing optical depth. This signal is detectable with a 4m class telescope and a modest observing campaign over a year, and provide a map of the underlying dark matter distribution. While chance alignments of HVCs with more distant galaxies are not common, several potential sources already present themselves. This situation is likely to improve as current data is scanned and future observations are undertaken. We eagerly await the monitoring of a 'mini halo' candidate HVC along the sight line to a nearby galaxy.

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